LA-UR -77-610

CONF-770313-

TITLE: MESON FACTORIES - 1977

AUTHOR(S): D. C. HAGERMAN

SUBMITTED TO: 1977 Particle Accelerator Conference
Pick-Congress Hotel
Chicago, Illinois
March 16-18, 1977

los alamos
scientific laboratory
of the University of California
LOS ALAMOS, NEW MEXICO 87544

Form No. 836
St. No. 2629

UNITED STATES
ENERGY RESEARCH AND
DEVELOPMENT ADMINISTRATION
CONTRACT W-7405-ENG. 36

MESON FACTORIES—1977*

by

Donald C. Hagerman
The Los Alamos Scientific Laboratory
P.O. Box 1663
Los Alamos, New Mexico 87545

Introduction

The history and rationale for the construction of meson factories is described in the excellent paper[1] of E. G. Michaelis presented during the 1975 conference of this series. Following his lead we define meson factories as accelerator facilities designed to produce 100 μA or more of proton current with an energy of 500 to 800 MeV.

The purpose of these facilities has been to provide large fluxes of pions and muons so that detailed and precise measurements of meson characteristics and meson interactions could be made. Such experiments are important in many fields of research and may well be of interest for various "practical" problems. Such accelerators are formidable undertakings; for example, the design currents for the existing machines imply beam powers of 50 to 800 kW and the associated very high levels of induced radioactivity.

The purpose of this paper is to compare the present level of performance of the existing machines. A preliminary section gives a brief description of the three meson factories in operation. Following the comparison of the existing machines the new Russian meson factory now under construction is briefly described.

Meson Factories in Operation

The Los Alamos Meson Physics Facility**[2] (LAMPF) was the first of the three operational meson factories to reach full energy in June 1972; by early 1974 a large experimental program was using the new facility. The first half of 1975 was used to make some needed changes in the accelerator; a low-current experimental program started again in the fall of 1975. The high-current experimental areas were substantially modified and upgraded during 1975 and early 1976; by spring 1976 the entire facility was back in operation.

The machine is a linear accelerator with a length of 800 m. Protons are injected at 750 keV, accelerated to 100 MeV in a drift-tube accelerator, and then to the maximum energy of 800 MeV in a side-coupled accelerator. H^+ and H^- beams are accelerated simultaneously. The output energy is continuously variable from 100 to 800 MeV but routine operation is nearly always at the highest possible energy in order to maximize meson production. The macroscopic beam duty factor is 6%. The experimental areas are extensive and designed to accommodate as many simultaneous users as possible. An overall view of the LAMPF facility is given in Fig. 1 and a floor plan of the experimental area is given in Fig. 2.

The Schweizerisches Institute für Nuklearforschung (SIN)[3,4] machine* first reached its full energy of 588 MeV in January 1974 with an extensive experimental program starting in the spring of 1975. The facility has not required any lengthy shutdown since startup; instead, they have continued to upgrade the facility by judicious use of short (two- to three-months) shutdowns. By late 1976 this machine was operating routinely at currents up to 50 μA.

The SIN machine is a combination of two isochronous cyclotrons. The low-energy cyclotron (72 MeV) is sector focused and uses either an internal or external ion source. This low-energy machine is used for low-energy research or as an injector to a ring cyclotron formed of eight separate sector magnets and four separate rf cavities. The maximum orbit radius in the injector cyclotron is 105 cm and in the ring cyclotron is 445 cm. The macroscopic beam duty factor is 100%. The experimental areas are immediately adjacent to the cyclotrons and the design was made to optimize the number of simultaneous users. A floor plan of the facility showing the accelerator and the experimental area is shown in Fig. 3.

The third machine is TRIUMF**[5,6] which is the meson facility of the University of Alberta, Simon Fraser University, University of Victoria, and the University of British Columbia. This machine first reached the design energy of 500 MeV in December 1974. The experimental program was started in the early spring of 1975. In late fall of 1975 difficulty was encountered with some of the rf resonator hardware but by February 1976 the machine showed a high level of success.

The TRIUMF machine is a sector-focused isochronous cyclotron using H^- atoms. The H^- beam is extracted by stripping to H^+ with a suitable foil placed at the appropriate radius in the cyclotron; this technique provides a continuously variable output energy as well as the option of simultaneously extracting two beams at different energies. The use of the H^- beam requires a large radius (7.8 m at 500 MeV) to avoid stripping by electromagnetic forces; further, a very good vacuum is required to avoid collisional stripping. Figure 4 shows the general layout of the TRIUMF facility. During 1977 they plan to increase the experimental area shielding so that it will be adequate for 100-μA routine operation; an improved beam dump, new neutron lines and other experimental area improvements will also be made.

Comparison of Existing Meson Factories

In any comparison of these facilities one must keep in mind that they are all relatively new and still in the

*Work performed under the auspices of the U.S. Research and Development Administration.
**Located at Los Alamos, New Mexico, U.S.A

*At Villigen near Zurich, Switzerland.
**At Vancouver, British Columbia, Canada.

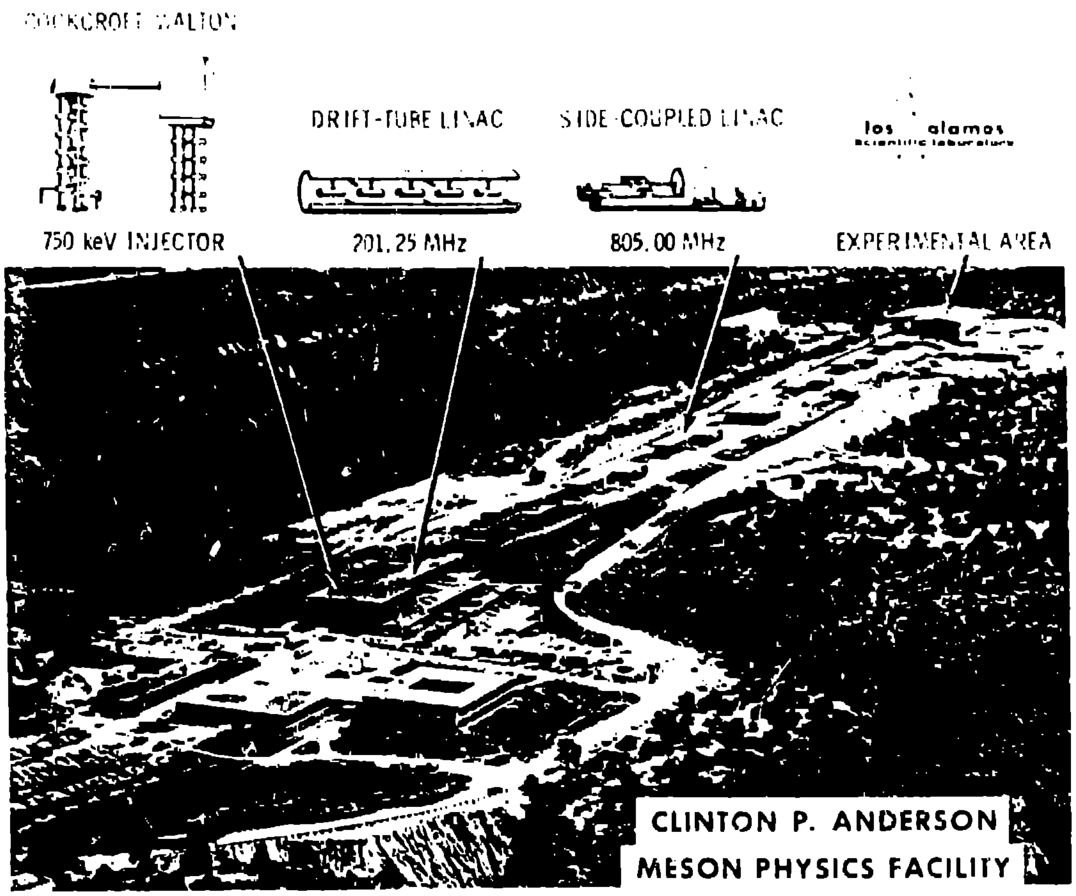

Fig. 1.
Aerial view of the Clinton P. Anderson Meson Physics Facility (LAMPF). The distance from the office building in the foreground to the beam stop is 1.1 km. There are three separate injectors (H^+, H^- and polarized H^-). The drift tube linac has an output energy of 100 MeV and the side-coupled linac an energy of 800 MeV.

developmental stage. The general approach at all of the facilities has been to first achieve a full-energy beam, next, start an experimental program at some low-current level, and then develop in parallel the capabilities of the accelerator, the experimental facility and the experimental program. As yet, none of the machines has reached its design goals for routine operation. The progress at all of the facilities has been good and the rate has probably been more strongly governed by funding than by extremely difficult technical problems.

The first comparison to make is the proton current available at the present facilities which is shown in Table I. In all cases the maximum test current has been at full energy with beam transported to the normal beam dump. Table I clearly shows that both SIN and LAMPF are high-current facilities now (i.e., meson factories) and they should be joined by TRIUMF within the year. At SIN there is a long-range study to investigate the feasibility of operating at currents greater than 100 μA.

A major consideration in the design of most experiments using these facilities is the macroscopic duty factor and rf structure of the proton beam. This information is given in Table II. For most electronic experiments a large duty-factor machine is an advantage: this problem is more important than anticipated by some a decade ago since electronic resolving times have not improved as much as expected. Yet, experiments with special background problems like some neutrino experiments are easier at the lower duty factors; as described later in this paper the Russian machine will apparently emphasize this type of experiment since their design duty factor is 1%.

TABLE I

PROTON CURRENT

	LAMPF	SIN	TRIUMF
Design Current (μA)	1000	100	100 ([illegible] MeV) 300 ([illegible] MeV)
Routine Operation (μA) (early 1977)	150	40-60	1-10
Expected Routine Operation (μA) (early 1978)	300	70	100
Maximum Test Current (μA) (early 1977)	200	112	80
Maximum energy (MeV)	800	590	520

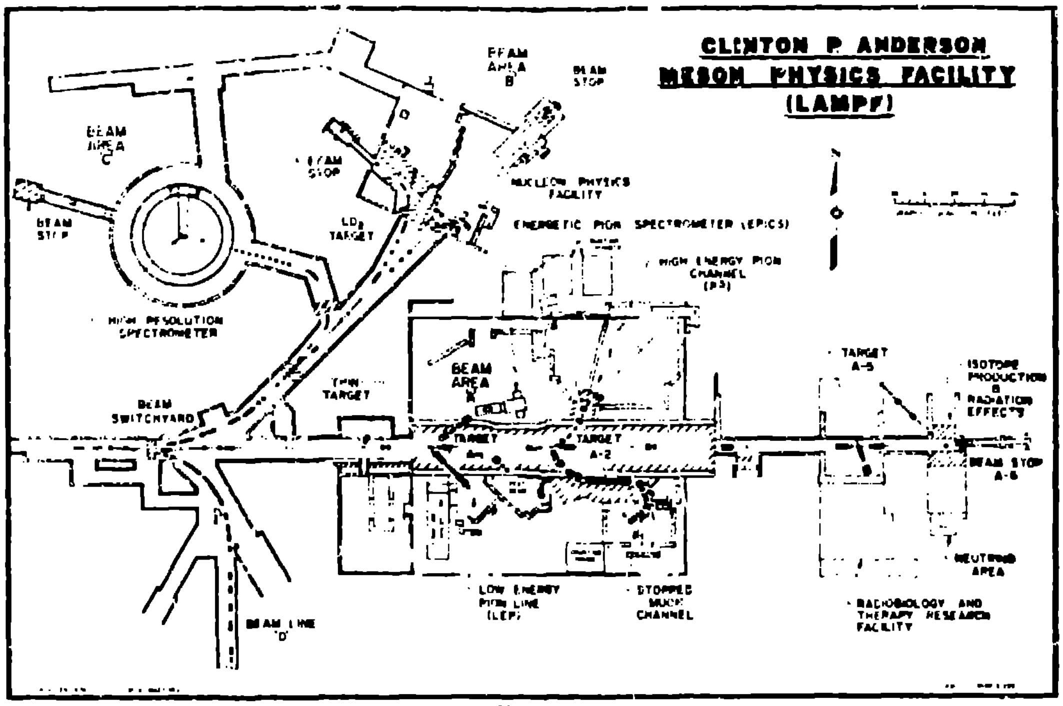

Fig. 2.
The LAMPF experimental area. The H⁻ beam, serves areas B and C. The H⁺ beam passes through targets A-1, A-2, A-5 and the isotope production facility to the A-6 beam stop. Line D uses the H⁺ beam on a time-shared basis.

An essential element in the design of all of these meson factories has been the need to maximize the number of simultaneous users of the facility. The initial impetus for this design constraint is the cost of operating any of the facilities which might well be deemed excessive if only a single experiment could be served at one time. The success of the designers in achieving high multiple use has been governed by a combination of technical problems and available construction funds. For example, a high-current target cell serving two or more beam lines with the appropriate transport system to reconstitute the beam after the target, adequate shielding, radiation hardened equipment, remote manipulator access and so on is a difficult engineering/applied physics problem as well as a very costly venture. The present level of development is shown in Table III. TRIUMF will be making some major revisions to their beam stop and experimental area in 1977; after these are completed the number of simultaneous users will increase to approximately 10.

From the vantage point of the user the beam availability and scheduled hours of beam per year are very important measures of the utility of the facility for experimental work. Again, the values attained in practice are some complicated function of available funds, technical difficulties and the amount of effort previously expended on technical problems. Table IV summarizes the present situation.

From the point-of-view of the accelerator designer the transmission through the machine is an important parameter. Transmission is obviously some measure of overall accelerator performance; for high-current machines transmission must be continually monitored

TABLE II

DUTY FACTOR

	LAMPF	SIN	TRIUMF
Macroscopic Duty Factor (%)	6%*	100%	100%
Pulse Length (µs)	500		
Microscopic Pulse Length (ns)	<0.3	0.5	4.0
Microscopic Beam Frequency (MHz)	201.25	50.6	23.1

*The plan to increase the LAMPF duty factor to 12% has been indefinitely postponed due to budgetary limitations.

TABLE III

EXPERIMENTAL AREA USE

No. of Experiments Simultaneously Receiving Beam	LAMPF	SIN	TRIUMF
Maximum	13	12	5
Typical	10	10	3

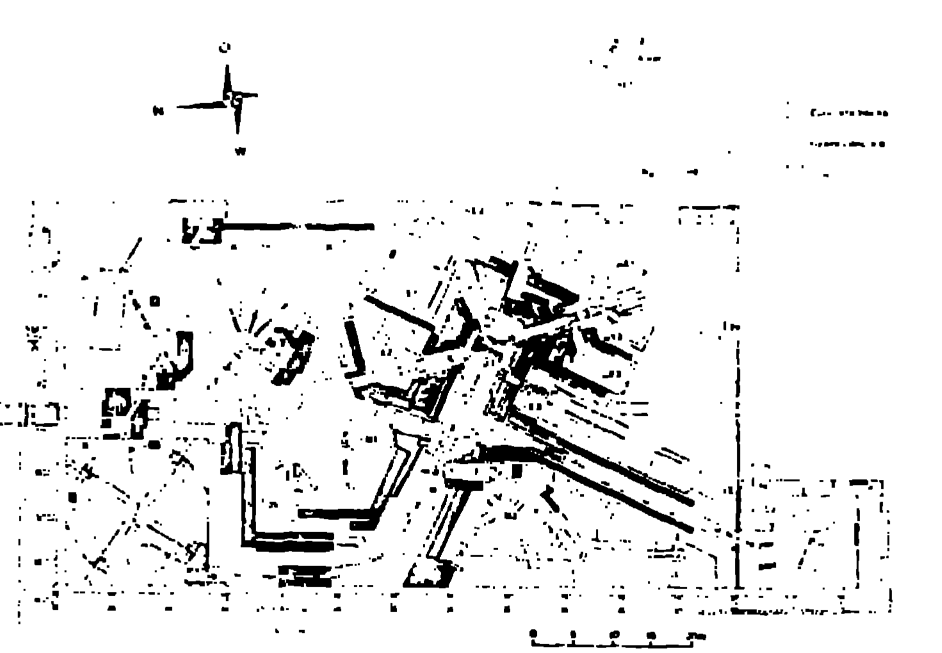

Fig. 3.
SIN Experimental Hall, floor plan 1976 with shielding. I injector cyclotron; R ring cyclotron; NEA and B low energy experimental areas; M thin, E thick meson production targets; πM1 high resolution pion beam with π-spectrometer; πM3 pion beam, pM1 beam line for scattered (polarized protons; πE1 pion beam with pair-spectrometer; πE2 short supercond. μ-channel; πE3 bio-medical πbeam; μE1, μE2, μE3 μ-beams from 8 m supercond. μ-channel; nE1, neutron beam; (nE2, direction of second neutron beam).

and kept within allowable bounds throughout production periods. At LAMPF and SIN it was assumed that transmission could be controlled well enough so that accelerator maintenance could be done either "hands on" as with local shielding and very simple forms of remote manipulators. Transmission at LAMPF and SIN in the high-energy portion of the machine (LAMPF 100 to 800 MeV, SIN 72 to 590 MeV) is better than 99%. At TRIUMF the transmission between 5 and 500 MeV is 75%. Beam losses at the lower energies are dominated by gas stripping of the H^- ions and at the higher energies electromagnetic stripping becomes important. To decrease gas stripping a better vacuum is needed and for this purpose large liquid helium-cooled cryopumps are being installed. Eventually the TRIUMF designers expect a transmission of approximately 86%.

At all of the facilities transmission and localized beam loss are carefully monitored by a variety of current measuring instruments and radiation detectors. For high average-current operation this sort of instrumentation is interlocked into the accelerator control circuitry so that the beam is automatically turned off in case of an unacceptable level of beam loss.

The dominant visual impression in the experimental area at either SIN or LAMPF is the enormous mass of shielding. The amount actually required around a target cell for meson production targets of significant thickness (~ 5 ... g/cm²) is in excess of 3 m of steel and perhaps a meter of concrete. For currents in excess of 100 μA this shielding is further complicated by the need for water cooling to carry off the heat deposited in the shielding by the beam scattered in the target. After a few months of operation the shielding near the target is activated at a high enough level so that it must be carefully handled when removed for maintenance. The shielding design must interact strongly with the secondary line design; particularly in regard to access for maintenance of the line. The general scheme at SIN has been to have the secondary lines removable as a unit via a railway system; at LAMPF access is provided via enormous doors which move ~ 10^3 tons of shielding out at a time. Recently, TRIUMF has received sufficient funds to install shielding adequate for 100 μA operation.

TABLE IV

SCHEDULED BEAM HOURS AND BEAM AVAILABILITY

	LAMPF	SIN	TRIUMF
Average Beam Availability (1976)	82%	86%[a]	77%
Accelerator Beam Hours For Experimental Program (1976)	4900	3070[a]	3650
Expected Accelerator Beam Hours for Experimental Program (1977)[c]	4000	3500	3620

[a] High energy operation only

[b] In 1976 the SIN injector cyclotron was run another 1000 hours for low-energy research; in 1977 they expect 1100 hours of low-energy operation.

[c] This number is the present estimate at the respective facilities.

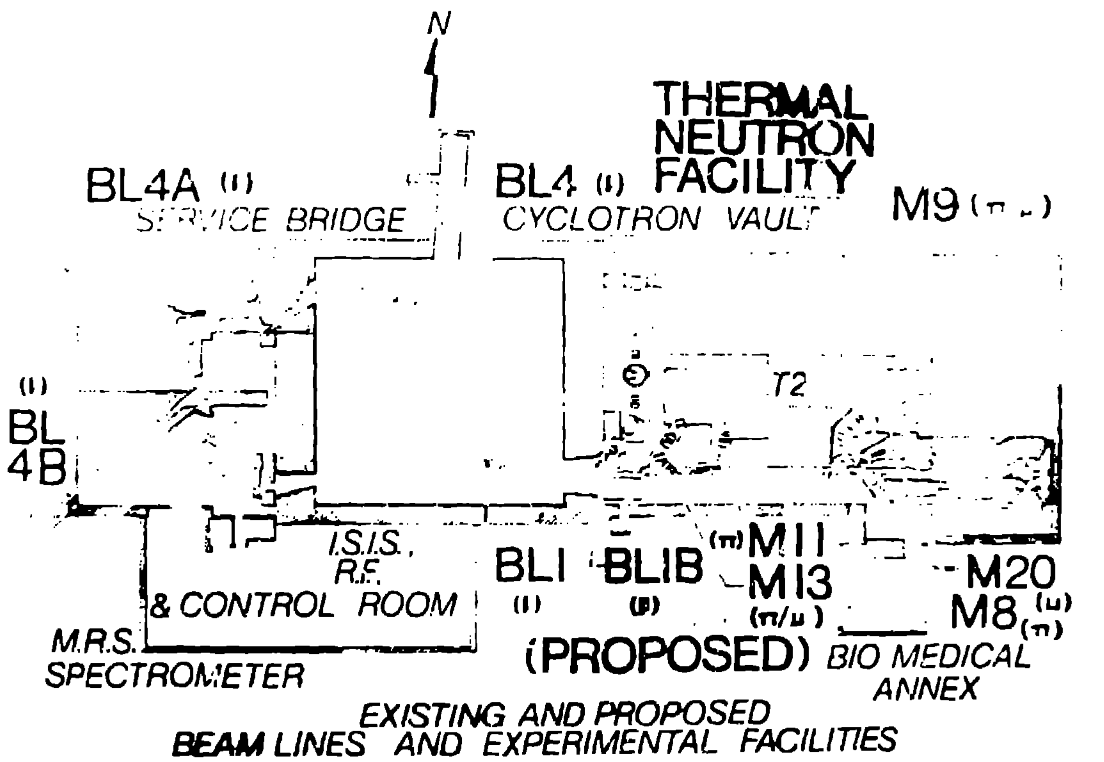

Fig. 4.
The TRIUMF accelerator and experimental facilities. The 520-MeV isochronous H^- cyclotron is at left-center of the figure. The proton areas are primarily at the left and the meson areas at the right of the cyclotron. The experimental facilities and shielding will be substantially enhanced during the mid-1977 improvement program.

Clearly, work on the targets and target-cell components which have been appreciably exposed to the beam requires remote handling facilities. At SIN the problem has been eased by the neighboring reactor institute; thus, target mechanisms are designed for easy removal and transported to the reactor facility with shielding casks for hot-cell work. At LAMPF local hot cells are provided and an increasingly sophisticated mobile remote manipulator system[7] is evolving for work directly in the hot cells. At TRIUMF special purpose remote manipulator systems are being developed; for example, a service bridge is being developed which can remove remotely any of the rf resonators in the cyclotron. Similarly, the lead shields needed for maintenance around the periphery of the cyclotron vacuum tank can be installed remotely. These manipulators rely on a digital locating system with video feedback for positional accuracy.

The power consumption at the facilities has become of interest because of the energy crisis and the ever increasing electrical power costs. Both TRIUMF and SIN are relatively modest in their energy consumption using 5.6 MW and 6.8 MW respectively. LAMPF suffers in this respect with a 27-MW load for full operation of the facility.

In addition to their primary purpose of providing intense meson beams all three facilities provide proton beams for different purposes. At TRIUMF the simultaneous production of two beams at different energies has been successful in permitting simultaneous meson experiments and proton experiments. The TRIUMF beam can be time chopped if desired. TRIUMF also provides a polarized proton beam of 30 to 50 nA. The SIN facility has the option of either polarized or unpolarized beams; the injector cyclotron runs alone nearly one-fourth of the time to provide proton beams for low-energy nuclear physics. The SIN beam can be time chopped at 200 kHz with a 50% duty factor, if desired. At LAMPF the simultaneous acceleration of H^+ and H^- beams permits flexibility in the structure of the H^- beam without compromising meson production. The H^- beam is split to serve three areas by stripping; it can be time chopped with 40- or 80-ns separation between micropulses. A polarized beam[8] should be in operation at LAMPF in the spring of 1977.

Lifetime and mechanical intensity of meson production targets[9] has long been of concern in the design of these facilities. However, experience shows that this problem has a variety of solutions up to 100 μA and the difficulties appear to be tractable at substantially higher currents. The high-current experience thus far has been almost entirely accumulated at SIN and LAMPF. At SIN targets of beryllium, carbon and molybdenum are used routinely; at LAMPF carbon targets are used exclusively. Cooling is accomplished by either radiation cooling or conduction to some water-cooled structure. Many of the radiation-cooled targets reduce the average local power by slowly rotating.

The Russian Meson Factory

The Institute for Nuclear Research at Moscow started building a meson factory[10] in October 1975 and they expect the first full-energy beam in 1981. The design energy is 600 MeV and with a maximum current of 500 μA. The machine will be a linac and the initial installation provides for a one-percent duty factor; the duty factor will eventually be increased to two-percent doubling the current to 1000 μA. H^- and H^+ ions will be accelerated simultaneously and eventually a polarized beam may be added.

Beams are injected into the linac at 750 keV. From 750 keV to 100 MeV a drift-tube structure will be used with rf stabilization provided via stabilizing posts in the plane of the support stems; the accelerating gradient in the drift-tube accelerator is 1.46 MeV/m. Between 100 and 600 MeV a $\pi/2$ mode accelerating structure[11] will be used of the "disc and washer" family; the bridge couplers will be rectangular in cross section. An accelerating gradient of 2.1 MeV/m is used in the high-energy portion of the machine. The operating frequency of the drift-tube accelerator is 198.2 MHz; the "disk and washer" will run at 991 MHz.

The rf system will have spare units which can be switched into service in the event of amplifier failure; this approach requires six 198.2-MHz amplifiers and 31 991-MHz amplifiers. A comprehensive computer control system will be used; conventional control is also provided on all systems.

They will use two production targets simultaneously which will rotate and be radiation cooled; target material will be either Mo or Al_2O_3. Remote handling facilities will be provided for the beam stop, targets, high-current beam transport and possibly the switchyard.

Conclusion

Over 15 years have passed since accelerator builders first seriously considered the problem of constructing meson factories. A large amount of effort, time and money have been expended in bringing the existing facilities to the present stage of development. Two of the facilities have already demonstrated operation at the 100-μA level and the third is not far behind. The success of these has prompted the construction of a fourth facility which should be in operation within a few years. It certainly appears plausible that one milliampere should be possible at both SIN and LAMPF. At TRIUMF the electromagnetic stripping will probably limit current to the few hundred microampere level in the long run. Thus, in many ways the expectations of the builders has been amply fulfilled.

Long-term operation of these facilities at high current may well introduce new problems in radiation damage of targets and beam stops. In any event the maintenance of these strongly radioactive areas will continue to provide a continuing challenge to the respective facilities.

The utility of these facilities to research cannot be evaluated with certainty until the experimental programs have flourished for many years. The situation looks very promising in the short term since at all of the facilities they have large and enthusiastic groups of users who are eager to exploit the new research areas unveiled by these facilities. Practical applications of the technology associated with these devices has already made a substantial impact on human affairs; an important example is the present generation of high voltage x-ray machines based on an accelerating structure developed for LAMPF. There is a very reasonable expectation that other associated practical applications will become important in the future; possible examples may be drawn from the radiation biology program at each of the existing facilities or the renewed interest in electronuclear breeding of reactor fuel.

Acknowledgement

The help of Dr. Hans Willax and his staff at SIN and Dr. J. T. Sample and his staff at TRIUMF has been invaluable in the preparation of this paper; at LAMPF I am indebted to many of my colleagues. In a paper of this length it is impossible to fairly represent the many technical achievements at these complicated facilities; any important omissions or errors in fact are my responsibility.

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